

Evaluation of the Stream Simulation Culvert Design Method in Western Washington, a preliminary study.

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Abstract

More than 50 stream simulation culverts have been constructed in Washington State since 1995. This paper summarizes monitoring conducted on 19 of these culverts in various settings. The monitoring goal was to compare the physical characteristics of the adjoining upstream channel with those of the culvert bed. The premise of stream simulation design is that similar physical characteristics imply similar passage conditions. Field parameters included channel geometry (channel width, slope and cross section, pool spacing, and residual pool depth) and sediment size distribution. Mathematical modeling using field data compared culvert and channel hydraulic performance including inlet contraction and depth distribution (quantification of shallow water habitat). Standard statistical tests were used to evaluate individual parameters, unfortunately the sample size was too small to perform multivariate analysis. Results show that when designed and constructed according to stream simulation design criteria (Culvert bed width = $1.2(\text{Channel width})+2$ feet, and slope of culvert $< 1.25(\text{Channel slope})$), stream simulation culverts are reliable and create similar passage conditions compared to the adjoining channel.

Introduction

Traditional culvert design methods for fish passage addressed the upstream passage of adult salmon¹. Clearly, this recognizes only one life phase of complex organisms and does not consider other species. A recent literature review concluded that stream dwelling salmonids are highly mobile and all species and age classes were observed to move upstream in all the studies designed to detect it¹⁶. Mongillo and Hallock (1997)²¹ noted that the distribution of nongame fish (*e.g.* sculpin) was affected by culverts and fish ladders designed for adult salmon. Remote habitats in headwater streams are important as refugia¹⁰ and fish passage through steep forest road crossings is increasingly important. Gradients in headwater streams can be very high and no acceptable design methods exist for these extreme cases. In order to provide upstream passage for juvenile salmonids and other fish life another design method is needed.

Traditional fish passage designs have been based on average velocity in the culvert. In order to determine such conditions for juveniles in corrugated culverts Powers and Bates²⁶ found that juvenile passage success decreased significantly at slopes greater than 0.2% and velocities greater than a third of a meter per second. It would be prohibitive to design a culvert using this standard. Allowable velocity for other species and age classes of fish are not well known. In addition, average velocity as a criteria for passage is too simplified and abstracted to capture the complexity of natural channel morphology and hydraulics⁴. The adaptation of fish to these conditions should be the basis for their free migration to all parts of the stream system. Therefore, a method that is based on average velocity may restrict upstream movement of some species.

The stream simulation culvert design method was created as an alternative to conventional methods to pass a wide variety of fish at high gradients. The basic concept of stream simulation is that fish have evolved to meet the passage challenges of natural channels and if we reproduce the chief characteristics of these structurally diverse and hydraulically rough channels inside the culvert, fish passage is implied, if not assured. The design uses the upstream channel as a reference and copies the slope and bed material. The width of the culvert is greater than the streambed width.

Application of the Stream Simulation Concept

Natural channels are dynamic systems^{18;30}. The health of the ecosystem that comprises the stream is dependant on this dynamism²⁸. The pattern of the bed, longitudinal profile and planform are continually modified at varying spatial and temporal scales^{5;30}. Stream crossings define a fixed point in this ever-changing system. At one end of the continuum is an undersized culvert, hydraulically smooth and fixed for its life span, which precludes any adjustments laterally or vertically. Such a culvert creates a hard point in the flexible fabric of the stream resulting in outfall drops, upstream gravel and debris deposits and extremes in velocity and depth in the barrel. On the other hand, a bridge with abutments set outside the channel migration zone will have less effect on channel processes.

The stream simulation concept is intended to take advantage of the cost savings of culverts yet allow many of the stream processes found in unconfined channels. Yet, stream simulation culverts cannot allow lateral migration or unlimited vertical variation. The premise is that these culverts will allow processes and hydraulic conditions important for fish and wildlife migration and the transport of water and materials downstream.

The stream simulation method of culvert design has two basic parameters, culvert bed width and slope. The complete design of a culvert is a complex affair involving bed material specification and adjustment in channel profile, among other issues, but slope and width are most fundamental. These parameters are a function of a representative reach where the culvert is situated. It is generally accepted that natural channels need width over and above the active channel to function normally¹⁸. The role and extent of this floodplain area decreases with increasing slope. Low gradient, main stem rivers have floodplains many times their channel width. Mountain headwater streams may have valley walls that extend nearly vertically above the toe of the bank with essentially no floodplain at all. Stream simulation was conceived initially to fill the niche created by small, steep, tributary channels where it was impossible to design culverts using existing methods (in addition to the reasons mentioned above). It was determined that some compromise must be made in order to design culverts that allowed stream functions at an acceptable cost.

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As defined by Bates et al¹, the design method uses the width of the bed inside a stream simulation culvert, $W_{\text{culvertbed}}$, as determined by

Equation 1

$$W_{\text{culvertbed}} = 1.2W_{\text{ch}} + C$$

where W_{ch} is the width of the natural streambed in a representative reach upstream of the culvert, and C is equal to 2 feet in English and 0.61 meters in the metric system. The result of this equation is rounded up to the next whole foot or 0.3 meter increment.

Constrictions occur naturally and are considered part of the normal stream continuum but they differ fundamentally from undersized culverts in two ways. First, a culvert is immobile and does not respond to hydraulic forces the way a stream channel would. Second, culvert inlet contraction is followed by a straight sided, solid boundary chute which confines turbulence and promotes sediment transport. Width ratio quantifies the constriction. The few recent studies of culvert performance^{27;34} have failed to consider the role of channel constriction.

The second criteria for a stream simulation culvert is that the culvert bed slope must not exceed the slope of the upstream channel by more than 25%.

The close association of average velocity with culvert design for fish passage in the past has led some²⁷ to consider only hydraulic conditions for evaluating culverts. Since the premise of stream simulation is based on natural channel conditions, this study concentrates on the physical characteristics of the channel inside the culvert.

As stated previously, fish have evolved to migrate in natural channels. They have developed strategies, most of which are unknown, utilizing natural channel features and their own abilities. Juvenile coho salmon were seen to overwhelmingly prefer the surface margin at the edge of a corrugated metal pipe²⁵. Stream edges are also thought to be migration corridors for juveniles when conditions along the thalweg exceed their swimming abilities. This study recognizes the importance of stream margins in migration and seeks to quantitatively assess the influence of culvert width on the development and maintenance of shallow water habitat inside the culvert. The method of depth distribution analysis was developed for this purpose.

For a culvert to truly replicate conditions in the natural channel, there must be a statistically significant correlation between reference reach conditions and those found in the channel.

Methods

Beginning in 1999 the hydraulic and physical characteristics of 15 culverts and associated stream channels in Western Washington were surveyed by various methods. There was a gradual change in survey scope over the years, from simply measuring channel and culvert

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basic geometry (slope and width) and sediment distribution, to an assessment of channel structure. These physical measurements assess directly the channel conditions presented to migrating fish and hold the most promise for effectiveness monitoring. Four culverts were added to the study in 2002 as well. This change in scope means that not all sample culverts have a complete set of data.

In the immediate vicinity of the culvert (approximately 300 ft), a survey of the culvert and channel was done with a laser level and fiberglass tape. Typical measurements included

- Culvert type and dimensions
- Culvert bed slope
- Upstream and downstream channel slope
- Culvert bed width at both the inlet and outlet (the horizontal distance between the points where the bed material meets the culvert wall).
- Two cross sections within the culvert.

Often the reach of stream immediately up and downstream of the culvert had been altered by the previous culvert's hydraulic control or by construction activity during the culvert installation. A reference reach was selected some distance upstream, outside this affected area. The reference reach represents average channel characteristics (slope, width and bed composition) and is relatively free of large wood or sharp bends. A laser level and fiberglass tape were used to measure slope and at least one representative cross section. Conventional stream survey techniques were used, such as Harrelson, *et. al.*, 1999¹². Bankfull width was either measured at the height of incipient flood³⁶ or through the use of bankfull indicators, such as the height of depositional features, a change in bank slope or undercuts in the bank¹². A minimum of 3 measurements were taken at carefully selected locations within the survey with at least one in the reference reach.

A pebble count was used to characterize the material in the culvert bed as well as the reference section upstream. The basic pebble count procedure used for this study was to string a measuring tape longitudinally down the stream channel and select one hundred stones below each regular interval (e.g. each foot mark) and measure and record their intermediate axis. This method is derived from Wolman³⁸, who described a grid method to create a random sample by selecting particles at regular intervals along the bed. Wohl *et. al.*³⁷ used a tape method although oriented the tape perpendicular to the length of the stream, spacing successive sample lines downstream at the sampling interval used to select the particles. While this method better represents the sediment population across the full channel cross section, it is confined to a relatively short section, possibly missing important features spaced at a longer interval than the length of the sampling grid.

The goal of this particular version of the pebble count is to characterize the general bed composition with the understanding that it is not strictly homogeneous (more than one channel unit is represented). Channels at slopes in the range of 3 to 8% typically have step pool configurations in which the largest particles generally occur in channel-wide steps²².

Figure 1 shows two tapes located at a spacing of approximately one third of the average

channel width of a step pool channel. The tape is pulled taut over the tops of all the rocks and then allowed to sag just enough to easily locate stones of all sizes below the increment marks. The procedure is conducted at low flow.

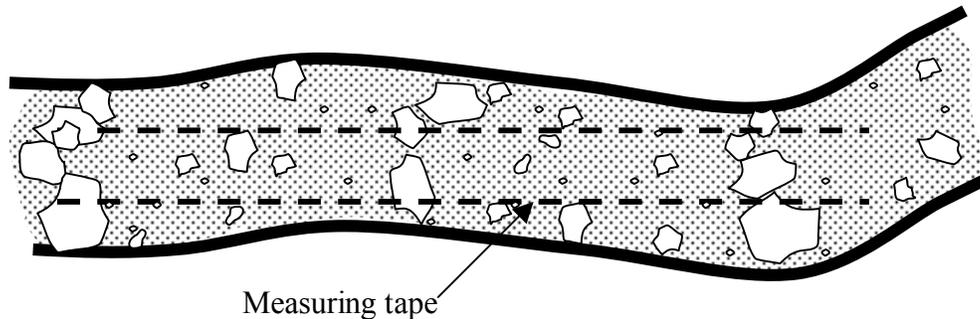


Figure 1 Pebble count method

The assumption is made that each sample point on the tape represents a random sample of a swath one increment long, perpendicular to the tape length and, in this case, one half the channel width wide. It is also assumed that the distribution of particles on a line perpendicular to the length of the stream does not change substantially from near-bank, to thalweg, to the other bank. This is mostly true for these headwater channels. The straight tape often approaches an undulating bank, improving the range of the sample. Since the steps in this type of channel are usually perpendicular to the channel length, this technique should, theoretically, give a representative sample of the whole channel bed in the reach.

Cascade channels are generally greater than 8% and are characterized by more disorganized bed material²², although partial-spanning bar or steps are common. This more disorganized structure with lateral elements lends itself well to the technique proposed here.

One foot increments have been used exclusively in this technique up to this point. Since 1.0 to 3.0 foot rocks consistently occupy a significant part of the channel area it seems likely that there is a statistical association between sampling increment and how truthfully the sample represents the parent group. Wohl et. al.³⁷ explored this by comparing two grid methods (as well as two other methods). One used a sampling increment equal to the intermediate axis of the largest clast found in the sampling reach, and the other using half that increment. In the second method, if the same rock appears beneath two successive increments, then it is counted twice. They found that there was no significant differences in the D_{50} and D_{84} determined by these two methods. The total distribution of particles did statistically differ. This may be attributable to fewer fine particles counted for a set sample size. In sampling, it is rare to encounter double counts and it has been customary to eliminate the second. Additional particles are added to make up for the reduced sample size.

In order to quantify the occurrence of stream edge habitat and relate it to width ratio the concept of depth distribution was developed. Each culvert and associated stream reference channel was modeled at the 10% exceedance flow (stream flow that is exceeded only 10% of the time in January) for the wet period of the year. This flow was chosen because of its general acceptance as an upper limit to conditions for which man-made structures are expected to provide good passage for adult fish¹. It is not expected that all species and age classes will choose to migrate at this flow.

The **Figure 2** illustrates the depth distribution in two extreme cases. Each stream is represented by cross sections from the culvert and the natural stream channel. The water surface at the 10% exceedance flow was determined using Jarrette's equation. Each wetted width was divided into 0.1 foot increments and the depth at each increment

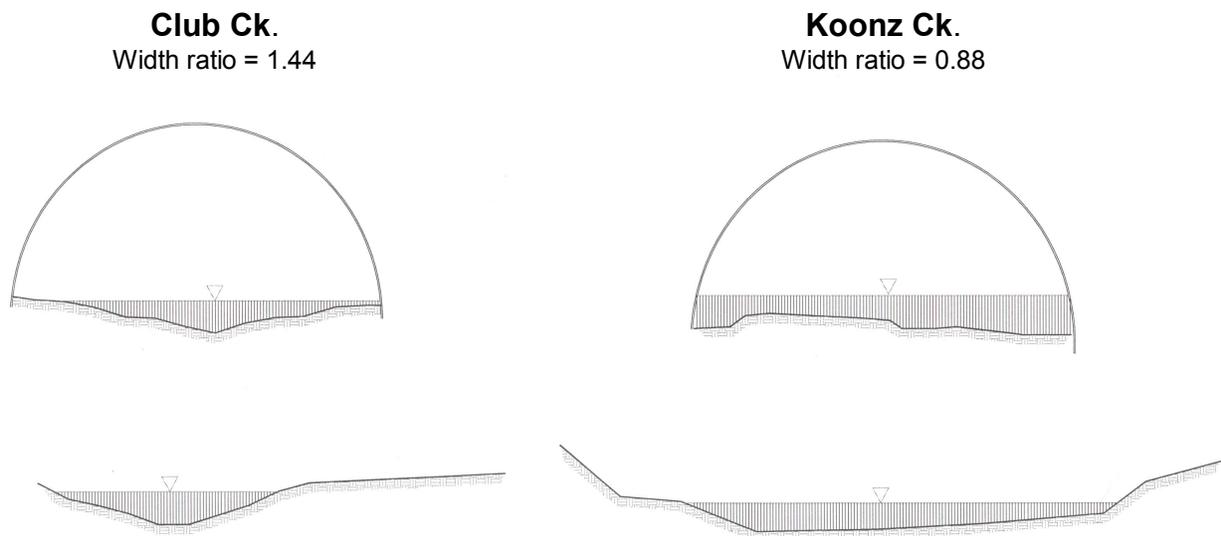


Figure 2 Depth distribution examples

tabulated. The frequency of each depth within 0.1 foot bins was then determined to arrive at a depth distribution.

To quantify edge habitat, sums of depths less than 0.3 feet were tabulated for the culvert and corresponding channel cross sections. These were combined into a depth distribution ratio where the sum of the depths in the culvert equal to or less than 0.3 feet in the culvert were divided by the similar sum in the channel cross section. This analysis does not recognize where edge habitat is within the channel; whether it is on the edge of the channel, on both banks, or whether it is continuous through the culvert.

As the study progressed it became clear that the development of channel features inside the culvert must be evaluated. Beginning in the spring of 2002 surveys measured channel structure using hip chain, stadia rod and clinometer. The technique used is similar to common stream habitat survey, for instance Pleus *et. al.*²⁵, although with less detail. A hip chain was used to determine the station of the pool centerline. While the center of a pool

is difficult to determine accurately, the exact location is not necessary to determine average characteristics. Pool tailouts and steps can be located more accurately although, as a class of channel features, they occur more frequently than pools in steeper streams.

Residual pool depth is the no-flow depth of the pool, found by subtracting the water depth at the tailout from the water depth in the pool. Residual pool depth is a measure of pool volume that is independent of flow at the time of the survey. See **Figure 3**.

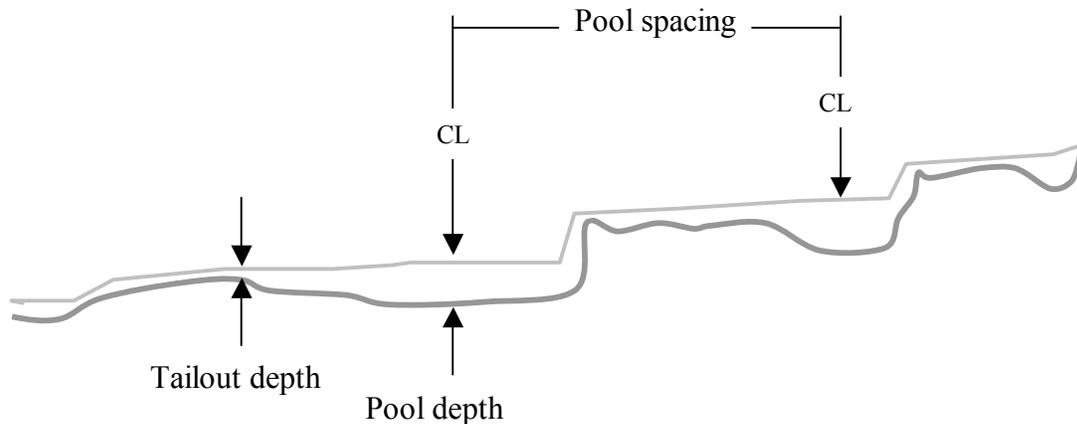


Figure 3 Channel survey method

Step and rough conditions present a unique challenge for hydraulic modeling. Traditional approaches to modeling open channel flow assume normal flow over a bed with low relative roughness. In rough channels the height of the larger bed materials is comparable with the flow depth and complex turbulence dominates the flow³⁵. A number of empirical and semi-empirical equations are available for an analysis of these conditions but they are crude with widely varying results^{2 13;15;19;23;32}. Jarrette's equation¹⁵ was chosen for use in this study for its ease of application. This equation predicts roughness as a function of stream slope, S , and hydraulic radius, R . In English units it is

Equation 2

$$n = 0.39S^{0.38}R^{-0.16}$$

In his 1984 paper, Jarrette limited its use to slopes between 0.02 and 0.04. Hubbard¹⁴ showed that this equation still predicted well on slopes up to 0.08, as well as or better than other, more complicated equations. It does tend to underestimate velocity where $R/D_{84} > 1$.

In this study only three reaches slope exceeded 0.08. Mussetter's somewhat more complicated roughness equation was applied to some of the study reaches. The results were not significantly different from Jarrette and it is suggested that the ease of Jarrette's equation outweighed the complexity of Mussetter.

Cross sections were taken inside the culvert and at a representative location in the adjacent channel. There were difficulties in obtaining a representative cross sections in the channel.

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These included an abundance of large wood in the channel, recent incision, and significant changes in channel type. Historically, large wood played a significant role in these channels. Most of the sample channels had wood, although its hydraulic effects, either by its presence or absence, was not addressed. Cross sections were analyzed using WinXSPro³³.

The 10-year peak flood flows was used in the average velocity and top width tests. It was chosen not because it is a flow associated with bed structure, but what could be reasonably modeled with the methods chosen^{14;15}. The work of Costa⁷, Grant¹¹, Chin⁶, and others indicate that bed changing events on high gradient streams are likely to be characterized by critical or supercritical flow. While it would be possible to model a cross section for average critical flow conditions, we know nothing about the vertical and horizontal velocity profiles that compose it. These profiles are likely to vary significantly from the low relative roughness paradigm of traditional hydraulics and should not be applied here.

For this analysis, it is assumed that if a given culvert shows increased hydraulic stresses over that of the natural channel at the 10-year event, then at the bed restructuring flow there will be a similar or greater increase in hydraulic conditions and therefore a change in the bed that may depart from reference reach conditions, defeating the purpose of stream simulation.

Reba²⁷ in her empirical study of culverts in the natural stream context, found no difference in velocity, or even a reduction in velocity, between culvert and natural channel. Unfortunately, her measurements were taken during a low flow period when the confining effects of the culvert are minimized.

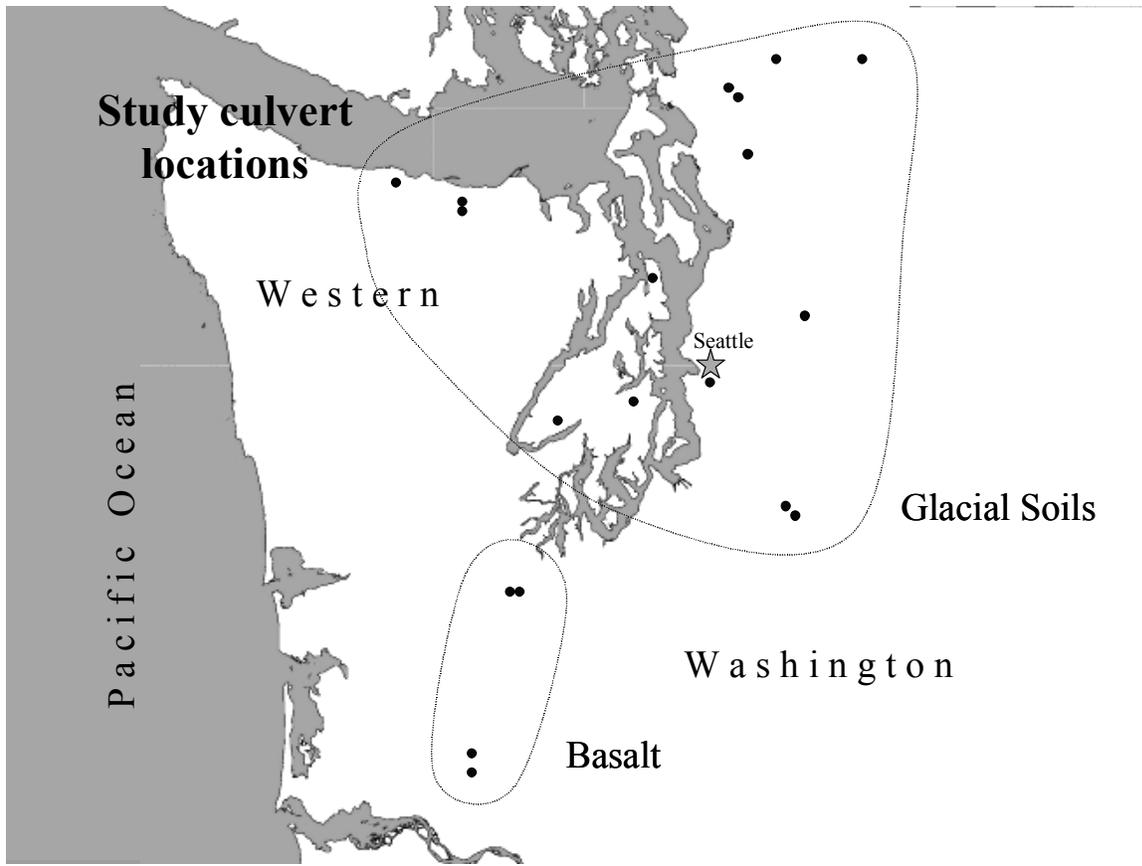


Figure 4 Study culvert location map

Study streams

A fairly large number of stream simulation-style culverts have been built in Washington, at least 27 were reported to have been built using the method described in the WDFW culvert manual¹ (the author keeps an informal database of this type of culvert with 59 records to date. Significantly more may be built without his knowledge). Nineteen Western Washington culverts were surveyed for this study, **Figure 4**. The oldest was built in 1995. Most culverts have experienced at least a 2 year recurrence interval storm, and four have experienced a 100 year event³¹. Most culvert shapes were closed, either box, pipe arch or round, so that bed material had to be placed inside. Bottomless culverts are also be designed by this method and two were in the study set. Length ranged from 30 to 120 feet, although length is not used as an independent variable in this analysis. Culvert length is currently an extremely important issue since the implications of length on bed stability and configuration are not yet understood.

Not all test methods were applied to all the culverts. As the study took shape, tests were added and modified as results indicated.

Most culverts were designed with some consideration of stream width. Ten were explicitly designed as stream simulation (using **Equation 1**), yet only 4 of these 10 succeeded in

meeting or exceeding the width criteria. Inaccurately measuring channel width is the likely reason the remaining 6 were designed narrower than **Equation 1**. The bed width of 8 of the pipes met or exceeded **Equation 1**. The remaining culverts were chosen for the study because they were steep (slope > 1%), wide relative to the channel, and were filled with bed material similar to the adjacent channel, as well as the need to test hypotheses through a range of variables. See **Table 1** for construction date, geometry, and hydrology information.

Table 1 Survey culverts and estimated flood flows.

Stream	Date installed	Culvert Shape	Span ft.	Length ft.	Q2 cfs	Q100 Cfs	HW cfs
Hooper Ck	1995	Round	12	66	30	93	50
Parker Ck.	1995	Box	24	61	51	155	NA
Pringle Ck	1998	Round	10	52	23	71	22
Trib. to Salt Ck	1999	Round	14	72	64	200	25
WF Stossel Ck	1997	Round	13	52	11	30	13
Trib. to Puget Sound	1998	Pipe arch	12	64	18	49	73
Trib. to Curley Ck	1998	Pipe arch	12	120	33	98	25
Kalawah Ck	1998	Pipe arch	9	30	39	123	NA
Stimson Ck, middle	1999	Round	10	74	17	56	21
Taylor Ck u/s	1999	Box	14	75	113	231	22
Little Mill Ck	1998	Arch	16	51	152	343	98
Round Knob Ck	1998	Arch	12	45	61	139	100
Koons Ck	1999	Pipe arch	13	50	47	138	90
Dead Man Flat Ck	1998	Arch	14	80	50	151	NA
Club Ck	1999	Pipe arch	12	60	26	80	21
Sherman Ck. Xtrib Abby	2001	Round	10	60	7	21	24
Sherman Ck. Xtrib Bea	2001	Round	13	62	12	37	53
Blue Siebert Alyce	2001	Round	10	50	8	22	21
Blue Siebert Betty	2001	Round	10	56	3	8	NA

Stream = Western Washington streams with stream simulation-style culverts.

Culvert shape = Cross sectional shape, a *pipe arch* is a squashed round and an *arch* is a bottomless half cylinder.

Span = maximum width of culvert cross section.

Q2 = The two year recurrence interval discharge determined from regional regression equations³¹

Q100 = The 100 year recurrence interval discharge determined from regional regression equations

HW = Estimated discharge determined from high water marks on the banks and attributable to a storm within the time period since culvert construction. NA, could not be determined with certainty.

These culverts have been mostly untested by storm events since construction. Fifteen of the 19 study culverts had observable high water marks from which discharge could be estimated using conventional slope-area methods or critical flow at obstructions or weirs. Four culverts experienced flows greater than or equal to the two year recurrence interval storm and four less than a two year event. One culvert was subjected to a dam break event that exceeded the 100 year event.

Results

Current trends in monitoring attempt to associate design goals or criteria with outcomes. Few of the culverts in this group were designed with clearly expressed goals so that this approach is not really appropriate. As a result, there are few references to original plans or goals. This monitoring seeks to evaluate the stream simulation design method as a passage strategy.

Width and slope ratios

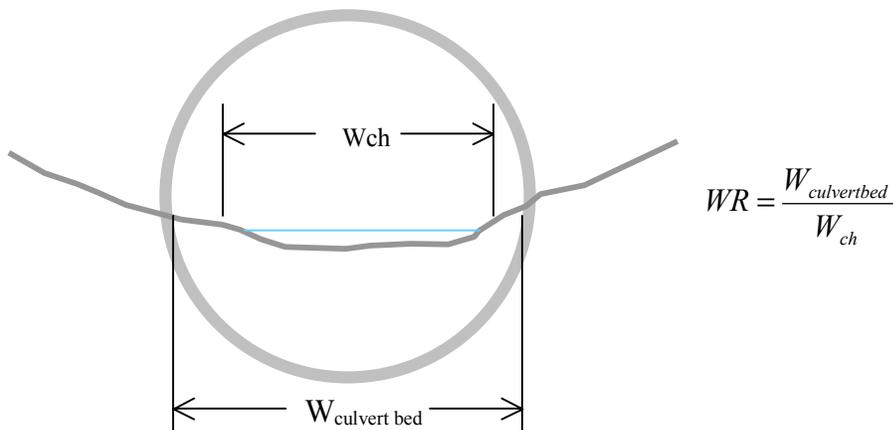


Figure 5 Width ratio

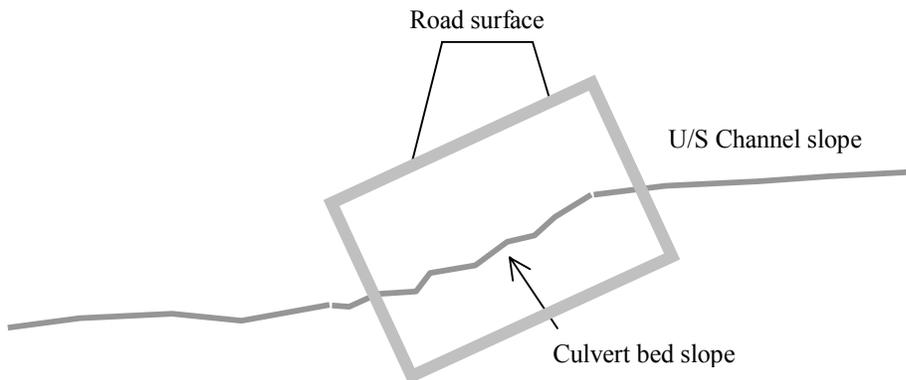
This study does not make use of **Equation 1**, rather it compares the width of the bed in the culvert, $W_{culvert\ bed}$, to that of the stream channel at the reference reach at bankfull stage as a ratio, W_{ch} , **Figure 5**. This **width ratio** (WR) is shown for each study site in

Table 2 and ranges from 0.9 to 1.8. In large part the analysis of the stream simulation culverts is based on this ratio since stream simulation culverts are designed using channel width. It is the intent of this study to show the relationship between width ratio and conditions inside the culvert. Culverts where $WR < 1.0$ act as constrictions (a distinct reduction in water surface width) at flows greater than the bankfull discharge.

Table 2 Width and slope ratios

Stream	W_{culvbed} Ft.	W_{chan} ft.	W_{culv}/W_{chan} Width ratio	S_{culvbed} ft/ft	S_{chan} ft/ft	S_{culv}/S_{chan} Slope ratio
Hooper Ck	11.4	8.7	1.3	0.050	0.048	1.0
Parker Ck.	24.1	15	1.6	0.013	0.027	0.5
Pringle Ck	9.3	9.1	1.0	0.060	0.050	1.2
Xtrib Salt Ck	12.75	11.6	1.1	0.029	0.023	1.3
WF Stossel Ck	12.25	7	1.8	0.064	0.040	1.6
Xtrib Puget Sound	12	7.4	1.6	0.020	0.030	0.7
Xtrib Curley Ck	11.7	10.7	1.1	0.025	0.020	1.3
Kalawah Ck	8.9	8.5	1.0	0.025	0.060	0.4
Stimson Ck, middle	9	8.7	1.0	0.022	0.020	1.1
Taylor Ck u/s	13.5	13	1.0	0.030	0.050	0.6
Little Mill Ck	15.3	14.7	1.0	0.042	0.045	0.9
Round Knob Ck	11.6	12.5	0.9	0.097	0.098	1.0
Koons Ck	12.6	14.4	0.9	0.021	0.040	0.5
Dead Man Flat Ck	13.6	NA	NA	0.061	NA	NA
Club Ck	11.5	8.5	1.4	0.068	0.130	0.5
Sherman Ck. Xtrib Abby	10	6.3	1.6	0.140	0.170	0.8
Sherman Ck. Xtrib Bea	13	9.5	1.4	0.110	0.130	0.8
Blue Siebert Alyce	9.7	8	1.2	0.037	0.040	0.9
Blue Siebert Betty	10	5.5	1.8	0.097	0.070	1.4

W_{culvbed} = width of the bed inside the culvert, the effective culvert “channel width.”
W_{chan} = the bankfull width of the channel.
S_{culvbed} = slope of the culvert bed.
S_{chan} = slope of the upstream channel bed.



$$SR = \frac{\text{Culvert Bed Slope}}{\text{U/S Channel Slope}}$$

Figure 6 Slope ratio

Slope ratio (SR) is the ratio of the culvert bed slope to the upstream (U/S) channel slope (outside the influence of the culvert, average of 200 feet upstream), see **Figure 6**. The upstream channel was chosen because it is least likely to have been affected by downstream incision and represents the slope associated with the type of bed material that supplies the culvert. When $SR = 1.0$ the culvert bed is placed at the same slope as the prevailing upstream channel slope.

Seven culvert beds were placed on a gradient steeper than the upstream channel, although only two with a slope ratio above 1.3, indicating that designers approached culvert slope conservatively. The WDFW stream simulation culvert design method recommends that the slope ratio be less than 1.25. This range is thought to be in keeping with “stream simulation,” since a radical change in slope represents an anomaly in local channel conditions. A large increase in slope will force supply limited conditions²², coarsening the bed, degradation, and little chance of rebuilding after storm events.

Sediment distribution

One way to gauge the hydraulic conditions inside a culvert is to look at the relative size of the bed material transported. Bedload transport equations commonly associate increasing shear stress or unit discharge with increasing D_{50} particle size^{3;6;24}. Thus a coarser median size of the culvert bed material indicates more severe conditions inside the culvert relative to the reference reach. This coarsening would also indicate a failure of the stream simulation concept since bed texture can be implicated in many morphological and habitat related functions^{4;17}, as well as movement of aquatic organisms²⁹.

Table 3 shows the effects of slope and width ratio on the relative size of the D_{50} particle. A t test for means was used to show the statistical relationship between the D_{50} found in the culvert to that of the upstream channel. With 95% confidence limits, half of the 16 analyzed culverts passed this test, showing a statistical similarity with the natural channel. Generally, those that are statistically similar have low slope ratios ($SR < 1.3$, with one exception), high width ratios ($WR > 1.0$), and appeared to be constructed in a way that considered native substrate. One exceptionally high slope ratio, WF Stossel Ck, also has the highest width ratio of the culverts studied and was constructed from material found in the bed below the original culvert. Of those that failed the t test, 4 must be considered outliers for reasons listed in Table 3. The other four were narrow ($WR < 1.1$). As a measure of relative size, the ratio of culvert to upstream particle size is used to normalize D_{50} and is also shown in the table.

Table 3 Culvert vs. channel D₅₀

Stream	Culv D50/ Chan D50	p(T<t)	Sculv/Schan Slope ratio	Wculv/Wchan Width ratio	Outliers
Koons Ck	0.5	0.000	0.53	0.9	
Hooper Ck	0.5	0.013	1.04	1.3	Bed retention weirs at surface
Little Mill Ck	0.6	0.008	0.94	1.0	
Club Ck	0.7	0.030	0.52	1.4	
Sherman Ck. Xtrib Bea	0.7	0.030	0.85	1.4	
WF Stossel Ck	0.8	0.239	1.60	1.8	
Xtrib Puget Sound	0.9	0.387	0.67	1.6	
Sherman Ck. Xtrib Abby	1.0	0.834	0.82	1.6	
Taylor Ck u/s	1.0	1.000	0.60	1.0	
Pringle Ck	1.2	0.325	1.20	1.0	
Xtrib Curley Ck	1.3	0.052	1.25	1.1	
Stimson Ck, middle	1.5	0.002	1.1 (2.5)*	1.0	
Xtrib Salt Ck	1.6	0.003	1.26	1.1	
Parker Ck.	2.2	0.001	0.48	1.6	Boulder controlled bed
Blue Siebert Alyce	4.2	0.000	0.93	1.2	Specified bed too coarse
Blue Siebert Betty	4.3	0.000	1.39	1.8	Specified bed too coarse

Culv D₅₀/Chan D₅₀ = Ratio of the D50 particle found in the culvert to the D50 particle found in the upstream channel.

p(T<t) = *t*-test for the statistical significance of the similarity of the means using ϕ values of mean and geometric standard deviation with a 95% confidence interval in a two-tailed test. Significance shown when p>0.025.

*Stimson was constructed at a high slope ratio, 2.5, and quickly regraded to a lower one. Width and slope ratio as previously defined.

Regression analysis did not show a statistically significant correlation between the D₅₀ ratio and width ratio (R squared = 0.06) with the outliers removed. Regression analysis did show a correlation between slope ratio and the D₅₀ ratio (R squared = 0.53) with the outliers mentioned above removed. WF Stossel Ck. was also removed because of a particularly large width ratio which creates a much wider and shallower flow pattern and a corresponding increase in relative roughness. **Figure 7** indicates that higher slope ratios tend to coarsen the transported bed material.

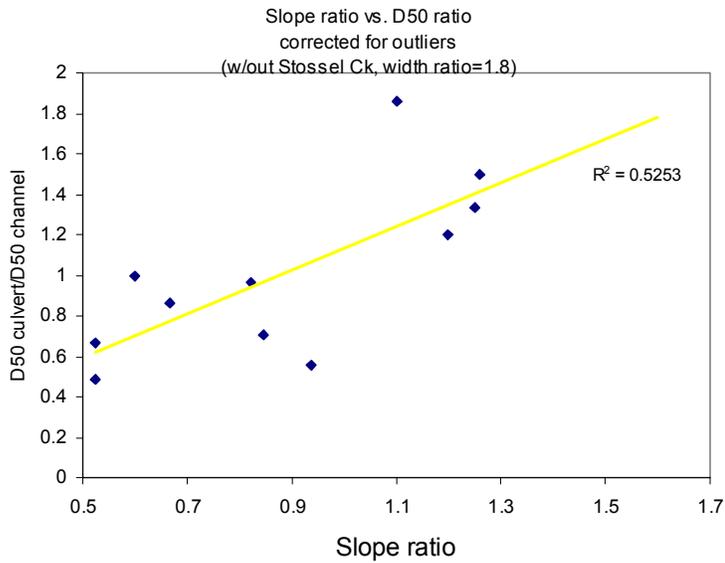


Figure 7 Slope ratio effects on D₅₀ ratio

Hydraulic modeling

Average velocity and top width were examined for this study to indicate the overall effect of channel and culvert cross section on hydraulic conditions. Average velocity is not related to fish passage but rather to cross section efficiency. The implication is that natural channels tend toward maximum roughness⁹ and a more efficient (higher average

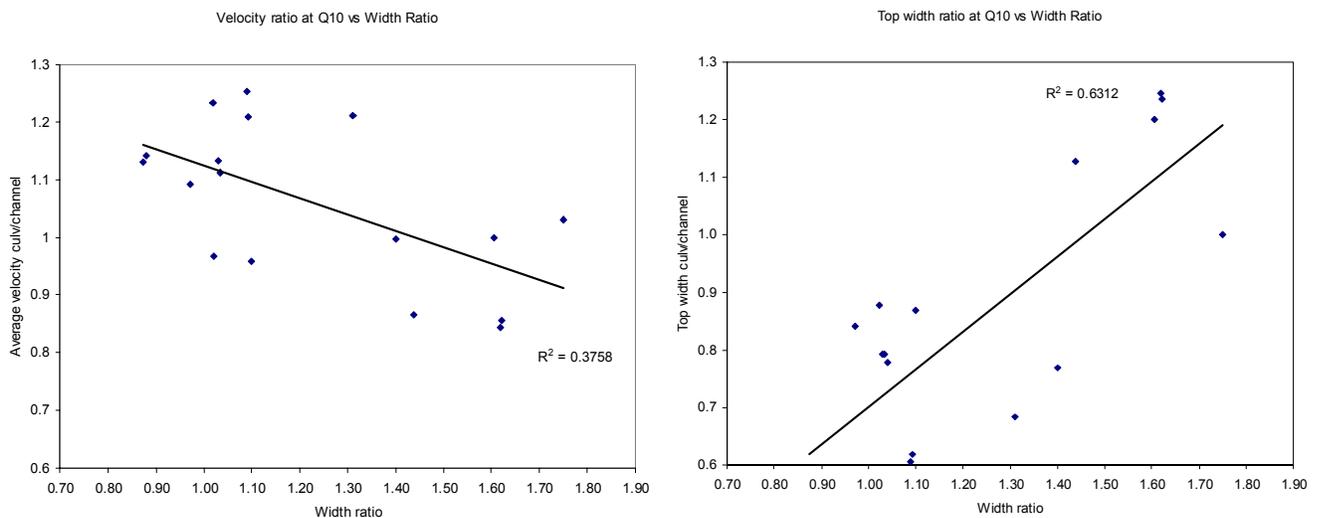


Figure 8 Width ratio effects on culvert hydraulics

velocity) culvert departs from reference conditions. Top width ratio is a measure of constriction. **Figure 8** shows the effects of width ratio on the ratios of average velocity and top width. The average velocity ratio is the average velocity of the modeled flow inside the culvert divided by the same parameter in the natural channel. When the average velocity ratio is less than 1.0 the velocity inside the culvert is less than the velocity in the channel at the same discharge. A similar ratio is used for top width. These dimensionless ratios are a way of normalizing the data so that comparisons can be made between streams and culverts of different dimensions.

These figures show a large amount of scatter. The variation in conditions at each site was significant. A range of cross sectional shapes were represented in the data with different stage-discharge relationships. The relative age of the channels varied, from beds recently carved into deposited material, to channels that have not changed in many decades. Vegetation, slope, and geology were different from site to site. These factors are difficult to model and lead to inaccuracies in the calculated hydraulics. In spite of this some reasonable conclusions can be drawn.

Average velocity ratio is somewhat insensitive to width ratio ($R^2 = 0.38$), as expected. Nevertheless, two groups of values are separated by the width ratio of 1.3. When culverts are 30% wider than the adjacent stream channel, average velocity is similar or less than natural conditions. At width ratios less than 1.3, average velocity tends to be similar or greater than the reference, conditions beyond stream simulation.

Top width ratio is much more sensitive to width ratio. This correspondence is less simplistic than it seems since top width inside the culvert is free to increase only until it encounters the wall of the culvert. Width ratios of up to 1.4 are required to prevent constriction at the 10 year event.

The regression lines show that as the width ratio increases hydraulic conditions inside the culvert become less severe relative to conditions in the natural channel.

Depth distribution analysis

During the initial stages of the survey two general categories of culvert bed emerged. Surveys for this study were done under base flow conditions and at this flow certain culvert beds were covered by flowing water from one wall to the other. Any increase in discharge over this base flow would result in a direct increase in depth and no increase in top width. Other culverts had dry margins inside that correspond to the bank lines that are present in natural channels at nearly all flows. Increased flow in these culverts results in a roughly log increase in depth and the persistence of low velocity margin areas that are thought to be important for both juvenile salmonid upstream passage and amphibian migration.

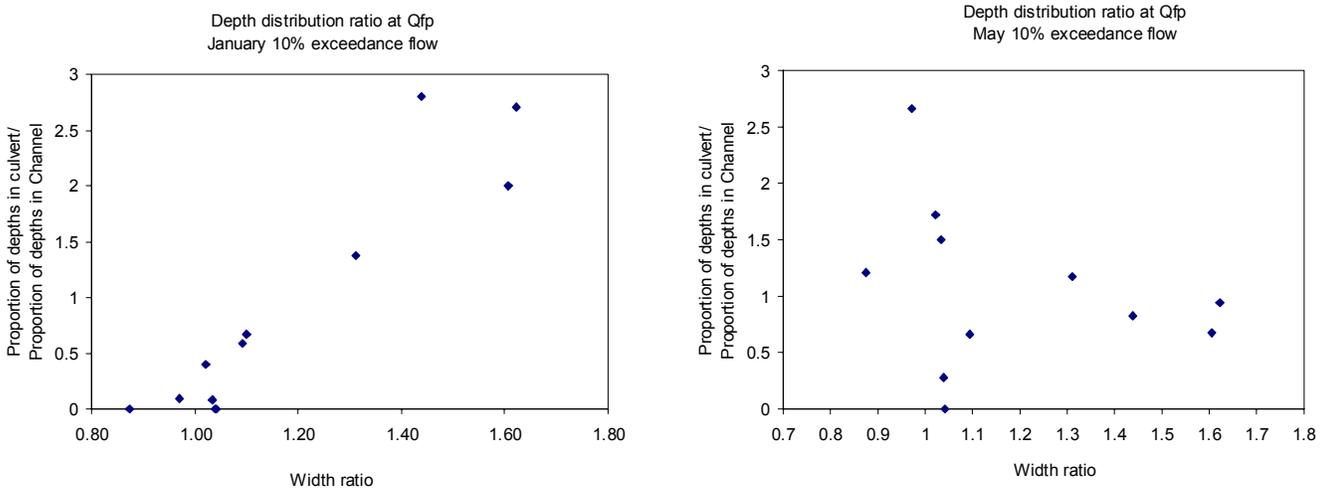


Figure 9 Depth distribution vs. width ratio.

Depth distribution analysis is summarized in **Figure 9**. The significance of the left hand chart, January flow, is that in order to preserve the shallow, low velocity edge habitat the width ratio must be significantly greater than 1.0. In this case, the width ratio must exceed 1.3 to create shallow water edge habitat in the same or greater proportion as that present in the natural channel. Many culverts preserved less than 75% and, in two instances, no shallow edges occurred. All these culverts had a span of at least 88% of the channel width.

At lower flows this effect begins to disappear. The next lowest flow for which we have regression equations is the 10% exceedance flow for May (16 to 33% of the flow used in the January analysis). The depth distribution summary for this flow is shown in right hand figure. Width ratio does not have much of an effect in this case. In fact, a few culverts show much more of this type of habitat than the natural channel. This is due to the fact that narrower culverts and culverts without forcing features such as debris and bank irregularities tend toward plain beds²² and therefore contain much more shallow water for a given flow.

As flow increases above what was modeled here, shallow edge habitat would decrease in even the widest culverts as depth rises up the culvert walls.

Pool spacing and residual depth

Table 4 Pool spacing

Creek Name	Pool Spacing		Difference Culv-Chan	p(Z< z)
	Log mean/Wch Culvert	Channel		
Xtrib Curley Ck.	0.8	1.7	-0.9	0.006
Alice Culvert	0.9	1.5	-0.6	0.008
Pringle Ck	0.7	1.3	-0.5	0.027
Koonz Ck	0.7	1.0	-0.4	0.073
Betty Culvert	2.4	2.5	-0.1	0.446
Club Ck.	0.8	0.9	-0.1	0.283
Bea Culvert	0.9	0.7	0.2	0.273
Xtrib Salt Ck.*	2.7	2.5	0.2	0.382
WF Stossel Ck.	1.5	1.0	0.5	0.112
Hoffman Rd.*	3.0	1.9	1.1	0.002
Abby Culvert	4.0	1.3	2.7	0.010

No pools occurred in the Taylor creek culvert. Hooper and Parker creeks removed because of rigid sills.

Log mean/Wch = log mean of pool spacing divided by bankful width of the channel.

* = arithmetic mean of pool spacing.

p = probability that there is no significant difference between the culvert pool spacing and the natural channel pool spacing. Two tailed Z test, alpha = 0.05, significance shown when p>0.025.

Pool spacing and residual depth are measures of complexity in natural channels. This complexity has both hydraulic and habitat benefits and might be a direct indicator of what we mean by “stream processes” when describing the continuity provided by the stream simulation culvert design method in some types of channels. In self-forming channels the bedform spacing/height ratio tends toward a value where roughness is maximized, with minimum mean velocity and maximum flow depth⁸. Fish and other organisms evolve to take advantage of these natural conditions which we are trying to simulate. In this context, pool spacing and depth are fundamental channel parameters. For a culvert to truly replicate conditions in the natural channel, there must be a statistically significant correlation between pool spacing and depth in both situations.

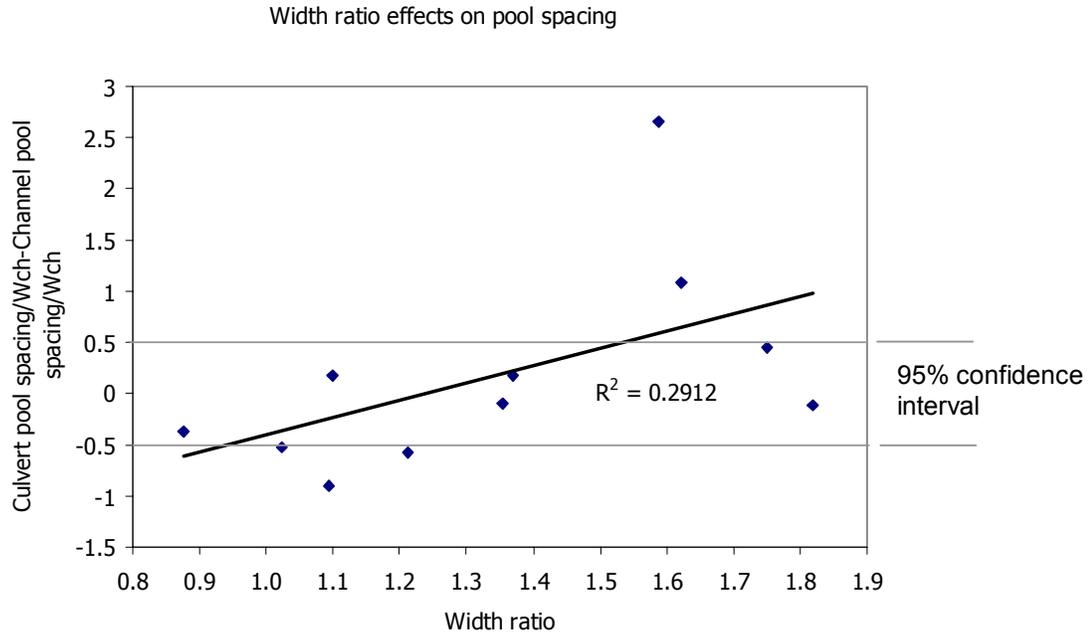


Figure 10 Width effects on pool spacing

Standard statistical analysis takes into consideration the number of samples. On average, only 4 pools occurred inside the culvert. Such a small number of sample point tends to broaden the confidence interval and lump most of the culverts into a category that shows statistical significance.

Figure 10 shows a weak relationship between the difference in normalized pool spacing (pool spacing/bankful channel width) and width ratio. A difference of pool spacing was used because a ratio of ratios cancels the normalizing effects of channel width. The author has noticed that narrow culverts that still retain native gravel beds tend to have to have a plain bed structure, with a flat, pool-free profile. This reflects a confined, low resistance, high unit discharge environment. It stands to reason that narrower culverts, relative to the width of channel, would have more closely spaced pools.

Residual pool depths in the natural channels studied show a large variation. This wide variation combined with the low sample number described above, lead to Z-test results that show no significant difference between the group of culvert residual depths and those found in the section of the natural channel sampled, see **Table 5**. Except in the case of Hooper Ck., which contains a significantly smaller substrate as well as three steel bed controls which force plunge pool formation.

Generally, pools tend to be shallower than in the natural channel. Without Hooper Creek (with steel weirs), culvert pools tend to be 36% shallower than those found in the natural channel, **Table 5**. The culvert beds are new and may not have had time to develop pool

depth. There is also the connection, yet unexplored, between sediment distribution and pool depth.

Table 5 Residual depth

Creek Name	Avg Resid Depth		Difference	Std Dev	
	Channel	Culvert	Culv-Chan	Channel	$p(Z< z)$
Hooper Ck.	0.47	0.90	0.43	0.22	0.05
Xtrib Curley Ck.	0.50	0.31	-0.19	0.25	0.1
Parker Ck.	1.13	0.53	-0.60	0.29	>0.1
Hoffman Rd.	0.74	0.28	-0.46	0.80	>0.1
Betty Culvert	0.57	0.30	-0.27	0.21	>0.1
Alice Culvert	0.51	0.32	-0.19	0.64	>0.1
Koonz Ck	0.54	0.38	-0.16	0.19	>0.1
Bea Culvert	0.37	0.24	-0.13	0.25	>0.1
Club Ck.	0.46	0.34	-0.12	0.29	>0.1
Xtrib Salt Ck.	0.89	0.80	-0.09	0.32	>0.1
Pringle Ck	0.33	0.26	-0.07	0.35	>0.1
Abby Culvert	0.36	0.30	-0.06	0.23	>0.1
WF Stossel Ck.	0.33	0.29	-0.04	0.54	>0.1

No pools occurred in the Taylor creek culvert.

$p(Z<|z|)$ = probability that there is no significant difference between the culvert pool spacing and the natural channel pool spacing. Two tailed Z test, $\alpha = 0.05$, significance shown when $p>0.025$.

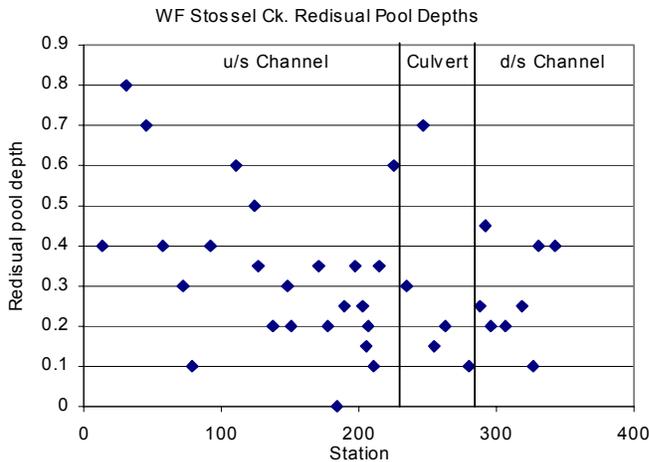


Figure 11 Residual depths in WF Stossel Ck.

Figure 11 is a sample residual depth survey, with residual pool depths as they occur along the channel profile. The large variation is typical. Some very shallow residual depths indicate small pools. But others are a result of porous tailouts or steps, composed of very coarse materials, than develop larger volume only with increased flow. WF Stossel is the oldest culvert in the pool survey and shows similar variation to the natural channel although a slightly lower average depth.

Bed failures

Four of the study culverts experienced significant changes in bed elevation and slope since construction, **Table 6**. These changes occurred after relatively minor storms in culverts that were generally narrow ($WR \sim 1.0$) and oversteepened ($SR > 1.25$). Culvert bed material, as characterized by D_{84} , varied for each case. D_{84} ratio represents current, post-regrade, conditions. Xtribs Curley and salt are armored. Little Mill Ck. experienced general, channel-wide scour. In the cases of Xtribs Curley and Salt, weirs were placed directly upstream of the culvert inlet, inducing sediment movement from excessive turbulence created by the plunge confined in the culvert.

Table 6 Bed failures

Stream	Slope ratio*	Width Ratio	D_{84} ratio	QHW	Comments
Xtrib Salt Ck	3.2	1.1	1.8	<Q2	Weir at inlet, high slope ratio
Xtrib Curley Ck	1.7	1.1	1.5	<Q2	Weir at inlet, high slope ratio
Stimson Ck	2.5	1.0	1.1	Q2	Culvert bed oversteepened
Little Mill Ck	0.9	1.0	0.7	Q2	Failed nick point, incising channel

* Slope ratio after construction, before regrade.

D_{84} ratio = the D_{84} found in the culvert/ D_{84} in the upstream channel at time of survey.

QHW = recurrence interval flood culvert has experienced since construction, e.g. Q2 = the two year flood, as determined from high water marks and hydraulic modeling.

Conclusions

This study attempted to compare culvert characteristics with a reference reach in the natural upstream channel. The implication is that if the channel inside the culvert is similar to the upstream reference then it accomplishes the goal of stream simulation. The measurements and analysis were selected to capture chief channel characteristics, not to determine whether a given culvert was “passable” to fish.

In general, if width ratio is greater than 1.3 and slope ratio less than about 1.3, the stream simulation culvert design method appears to successfully reproduce natural channel conditions inside the culvert for the channel types studied (moderately entrenched, coarse-bedded streams). In particular:

- **Sediment distribution** Slope ratios greater than about 1.1 tend to coarsen the bed material.
- **Hydraulic modeling** Average velocity is negatively correlated with width ratio. Culvert width ratios less than 1.4 act as a constriction during storm events.
- **Depth distribution** The area of shallow depth at the January 10% exceedance flow equaled or exceeded that of natural channels when the width ratio is greater than 1.3. This type of habitat was limited or excluded when width ratios were less than 1.2.

- **Pool spacing and residual depth** Seven of the 11 culverts have statistically similar pool spacing to the natural channel. High variance and small sample number resulted in no statistical conclusions concerning the similarity of culvert residual pool depth with that found in the natural channel. Culvert pool depths are within normal variation found in the natural channel. Indications are that culverts can develop natural channel features and that the stream simulation concept can be successful in this respect. Monitoring over a longer time frame will show whether repeated flows enhance or depress these pools.
- **Bed failure** Oversteepened and narrow culverts with small sediment and upstream weirs lead to bed failure.

Unfortunately for this study, the development of channel structure takes place over a rather long period of time in response to repeated bed changing flows²⁰. In this context, many of the channels themselves are new and the oldest of the culverts in the table above was built in 1997.

An expanded study must be undertaken to refine the relationship between channel width, floodplain width and culvert bed width, along with the complicating effects of bed material composition and slope ratio. The exact number of culverts necessary for this larger study has not been determined, although the relatively small number of possible subject culverts in Washington would lead to using all, or a significant number, of them. Further study must extend the stream simulation culvert method to other channel types in different hydrogeographic areas, especially the arid west and older geologies in the East.

The identification of hidden stream crossing effects, such as substrate discontinuities and temperature barriers, and their effects on stream ecology, underscores the need to reliably design culverts that simulate stream processes. Add benefits will occur if future monitoring is associated with migration studies of non-salmonid fish and other aquatic species. Without an expanded study, we will not be able to make conclusive statements about the success of stream simulation culvert design.

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